Optically Activated $ZnO/SiO_2/Si$ Cantilever Beams

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Abstract

The photomechanical effect induced by periodically varying sub-bandgap illumination in thin ZnO films deposited on oxidized Si has been demonstrated for the first time. The efficiency of this effect is at least one order of magnitude higher as compared to the photothermal activation of Si. Thus it can be considered as a powerful optical drive for resonant sensors. A phenomenological model of the mechanisms involved in the process is proposed. The optomechanical effect can also be used as a complementary method in determination of the surface state parameters of ZnO films.

Introduction

It has been shown [1–3] that in a depleted surface layer of polar semiconductors, piezoelectric coupling of electrical and mechanical properties can result in important photomechanical effects produced by light-induced electronic transitions. These effects were successfully studied in (001) CdS, (111) GaAs and (001) ZnO monocrystals by surface photovoltage spectroscopy. This technique is based on the photostimulated depopulation and population of surface states by sub-bandgap illumination, while the overall number of bulk free carriers remains unchanged. Under such illumination, the barrier height of the depleted layer can be modified, which in turn results in a variation of the surface stress. In the case when the barrier height is periodically varying, the surface stress also varies periodically. If the frequency of the variation of the surface barrier is close to the natural frequency of a beam, a resonant vibration is obtained. In a photomechanical vibration, the periodic change of the surface barrier is equal to the surface photovoltage [1].

The photomechanical effect is consistent with the surface piezoelectric effect, where the external stress applied to polar semiconductors leads to a modification of the surface barrier height and causes pronounced changes in the contact potential difference [4]. Since sub-band low-intensity light is used in these experiments, contributions of thermoelastic or pyroelectric effects to the photomechanical effect are not likely.

Surface photovoltage spectroscopy associated with photomechanical effects has been used to study the surface properties of non-centrosymmetric semiconductors exhibiting a depleted surface layer [3].

In the present paper, the photomechanical effect has been employed to produce photostimulated vibrations of Si cantilever beams with a thin film of polycrystalline ZnO. Experimental results will be compared with theoretical evaluations of the processes involved. The efficiency of the effect will be compared with that of the light-induced vibrations (photothermal effect) in Si beams.

Experimental

Thermally oxidized ($t_{ox} = 10\,000$ Å) Si cantilever beams, $10 \times 1.5 \times 0.05$ mm and $5 \times 1.5 \times 0.05$ mm in size, were covered with a 5 μm thick ZnO layer. The films were r.f. planar magnetron sputtered from a Zn target in a pure oxygen atmosphere. The sputtering equipment at the University of Twente is described in detail by Horsthuis [5], who determined the optimum deposition parameters to obtain dense, smooth and highly oriented layers. The following parameters were used:

substrate temperature $T_s = 400–450$ °C;
r.f. forward sputter power $P = 1800$ W;
oxygen pressure $P_{ox} = 8.6 \times 10^{-3}$ mbar;
target–substrate distance $tsd = 45$ mm.

Extensive studies on the structural, electric and piezoelectric properties of the ZnO films have

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been carried out by Blom and van de Pol [6–7]. They proposed a conduction model for polycrystalline ZnO films, based on models for polycrystalline semiconductors. According to this model, the film consists of columnar grains with semiconducting kernels and completely depleted boundary regions. In order to verify the model, current–voltage, capacitance–voltage and van der Pauw measurements were performed. The following electrical parameters were deduced:

free electron concentration $n = 5 \times 10^{23}\ \mathrm{m}^{-3}$ ($\pm 50\%$);
density of trapping states $N_t = 5 \times 10^{16}\ \mathrm{m}^{-2}$ ($\pm 50\%$);
Schottky barrier height $\Phi_b = 1.2 \pm 0.2$ eV;
depletion layer thickness $L_c = 80$ nm;
resistivity in the kernel $\rho = 5\ \Omega$ m ($\pm 40\%$);
electron mobility in the kernel $\mu = 3 \times 10^{-6}$ $\mathrm{m^2/V\ s}$.

The piezoelectric properties of ZnO at low frequencies were explained using a depletion layer approximation by these authors.

Beams were activated via an optical fibre held close to the clamping edge of the beam and connected by the other end to a laser source of sub-bandgap illumination, i.e., the energy of light was lower than 3.3 eV. The frequencies of the light modulation were equal to the natural frequencies of the beams and achieved using an electro-optic or acousto-optic modulator inserted into the optical path. The beam deflection was measured using a simple multimode optical fibre connected to a LED and hold close to the free end of the beam used as a moving mirror. The reflected intensity passing back into the fibre was modulated by the beam vibration and a suitable filtering of the output signal resulted in a resolution better than 1 nm of the peak deflection. The experimental set-up is shown in Fig. 1; all measurements were carried out in air and at room temperature.

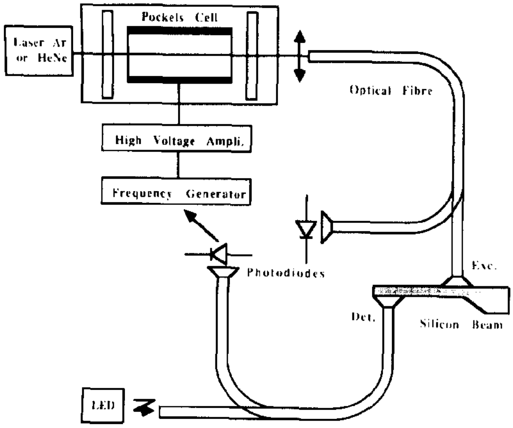

Fig. 1. Schematic representation of the experimental set-up used in this work.

Theory

A phenomenological model of the photomechanical effect has been developed by Lagowski and Gatos [1]. In this model, the piezoelectric contribution to the surface stress induced by interaction of the static sub-bandgap illumination with the surface states was evaluated. An approximate formula giving the amplitude of vibration produced by the periodically varying surface electric field was expressed in terms of the relevant piezoelectric coefficient d_{31} and the barrier height change ΔV_s [1]. This formula is valid for monolithic samples.

To explain the experimental results in this work, a theoretical approach concerning the dynamic behaviour of beams subjected to periodically varying illumination had to be developed. This can be separated into four sections:

(i) Solution of Poisson's equation for the depleted layer, which gives the value of the surface barrier height v_s.

(ii) Solution of the rate equation $dn_t/dt = -K_{ph} I n_t$ during the time when the light is on. As a result the barrier change ΔV_s can be obtained. In this equation K_{ph} is a capture cross-section of surface states for photons during surface state depopulation and I is the number of photons/$\mathrm{m^2}$ s.

(iii) Solution of the continuity equation during the time when the light is off. This is used to evaluate the frequency limit for the return of electrons at involved surface states.

(iv) Calculations of the vibration amplitude of the $Si/SiO_2/ZnO$ beam.

The following assumptions are made in treating the surface barrier height change quantitatively:

(a) there are no free holes either in the dark or under sub-band illumination, since an n-type large energy gap semiconductor is being considered;

(b) there is no formation of electron–hole pairs;

(c) there is a depletion layer at the surface;

(d) thermal generation of carriers and recombination transitions associated with an involved surface state are neglected as compared to a light-generation process.

Figure 2(a, b) shows a schematic representation of the photovoltaic process considered here and the energy-band diagram at the surface of the n-type semiconductor.

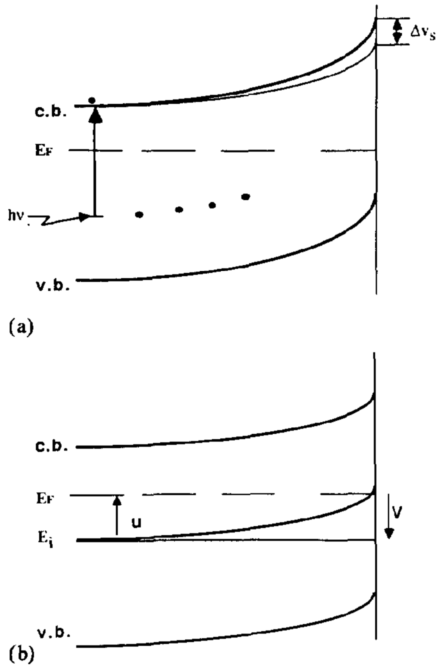

Fig. 2.(a) Schematic representation of the photovoltaic process in an n-type semiconductor with a depletion region: surface state depopulation. (b) Energy-band diagram considered in this work. All symbols are explained in the text.

The potential V as a function of distance can be obtained by using the one-dimensional Poisson equation:

$$V''(x) = -\frac{\rho(x)}{\epsilon} \tag{1}$$

where ϵ is the permittivity of the semiconductor and $\rho(x)$ is the total space-charge density. In the potential dimensionless notation the general equation has the form:

$$v''(x) = -\frac{q^2}{\epsilon kT(n_b - p_b + p_b \exp(-v) - n_b \exp(v))} \tag{2}$$

where $v = qV/kT$ and n_b and p_b are bulk concentrations of electrons and holes respectively.

The first integration from the bulk toward the surface gives the relation between the electric field and the potential v:

$$v'(x) = \frac{F(u_b, v)}{L} \tag{3}$$

where L (Debye length) and $F(u_b, v)$ are defined as follows:

$$L = \left(\frac{\epsilon kT}{q^2(n_b + p_b)}\right)^{1/2} \tag{4}$$

$$F(u_b, v) = \sqrt{2}\left[\frac{\mathrm{ch}(u_b + v)}{\mathrm{ch}(u_b)} - v\,\mathrm{th}(u_b) - 1\right]^{1/2} \tag{5}$$

where $u_b = (E_F - E_i)/kT$.

By Gauss's law, the space charge per unit area required to produce the electric field equals

$$Q_{sc} = Lqn_bF(u_b, v_b), \quad p_b = 0 \tag{6}$$

The barrier height variation induced by the periodically modulated light can be obtained from the rate equation which, according to our assumptions, contains only one term related to the light-induced depopulation of the surface level:

$$\frac{dn_t}{dt} = -K_{ph}n_tI \tag{7}$$

According to eqn. (6) the variation of the occupied surface states will be

$$F(u_b, v_s^0 + \Delta v_s) - F(u_b, v_s^0) = F'(u_b, v_s^0)\,\Delta v_s = \frac{K_{ph}n_t^0 I}{fLn_b} \tag{8}$$

where f is the light modulation frequency and v_s^0 and n_t^0 are the potential and surface state occupation at electrostatic equilibrium conditions respectively.

Δv_s can be calculated from this equation and is equal to:

$$\Delta v_s = \frac{K_{ph}IN_t^2}{fL^2n_b^2\left[\dfrac{\mathrm{sh}(u_b + v_s^0)}{\mathrm{ch}(u_b)} - \mathrm{th}(u_b)\right]} \times [1 + \exp(p_0 - u_b - v_s^0)] \times [1 + \exp(p_\lambda - u_b - v_s^0)] \tag{9}$$

where

$$p_\lambda = \frac{Eg}{2kT} - \frac{hc}{kT\lambda},$$

$p_0 = (E_t - E_i)/kT$, λ is a wavelength and N_t is the surface state concentration.

When the light is off, the carriers return to surface states via a diffusion process. The solution of the continuity equation shows that even for very low electron mobilities, the frequency limit is of the order of a few tenths of kHz, thus confirming the validity of the rate equation used in this work. Note that measurements of this frequency limit can give a good indication of the carrier mobility.

The amplitude of vibration was obtained using a model for beams composed of different materials [8], see Fig. 3. This amplitude is proportional to Δv_s and the piezo-electric coefficient d_{31}:

$$A = 3\frac{\Delta v_s d_{31} l^2 Q}{e^2} \tag{10}$$

where Q is the quality factor and l and e are the beam length and thickness respectively.

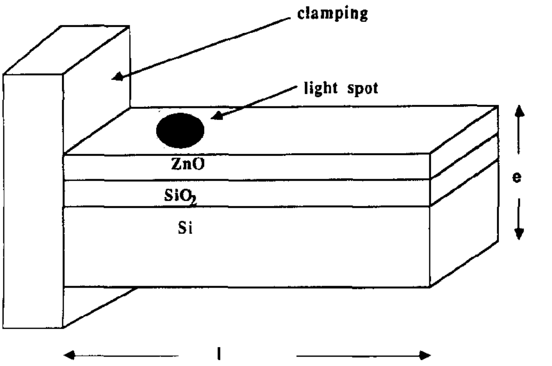

Fig. 3. Cantilever beam composed of three different materials.

Results and Discussion

A typical frequency response of a Si beam ($10 \times 1.5 \times 0.05$ mm) covered with a 5 μm thick ZnO film and activated using an argon laser beam ($\lambda \sim 520$ nm), is shown in Fig. 4. The Q factor obtained for this beam is about 200 and the peak-to-peak deflection was 160 nm for 130 μW peak-to-peak light power. The light spot area on the beam was about 2.5 mm^2. A linear dependence of the deflection amplitude on the light intensity was also observed, which is in agreement with eqn. (10). The optomechanical effect depends on the light energy $h\nu$ because the depopulation rates depend on the energy position of the surface states involved. This problem was extensively studied by Lagowski *et al.* [1, 2]. Their experimental results show that the amplitude of vibrations increases with the light energy $h\nu$. In this work, similar behaviour has been observed for discrete wavelengths ranging from 480 to 633 nm. In addition, the cantilever beams made from bare Si or covered with a thin Au layer were optically activated (photothermal effect in this case) in the same experimental conditions. The results are shown in Fig. 5. The observed amplitude ratio for the photomechanical and photothermal effects produced by the same light intensity was at least 10/1.

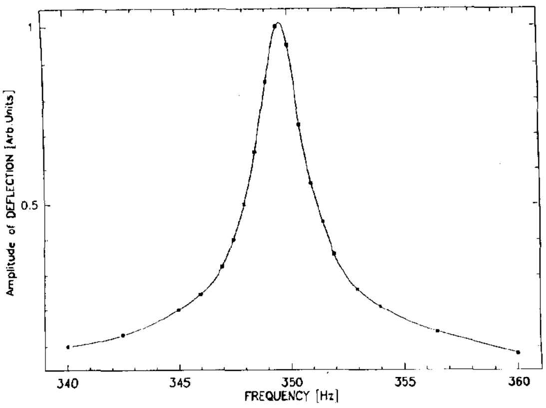

Fig. 4. Typical frequency response of a $ZnO/SiO_2/Si$ cantilever beam activated using an argon laser beam. Peak-to-peak power was 130 μW, deflection $d = 80$ nm, Q factor = 220.

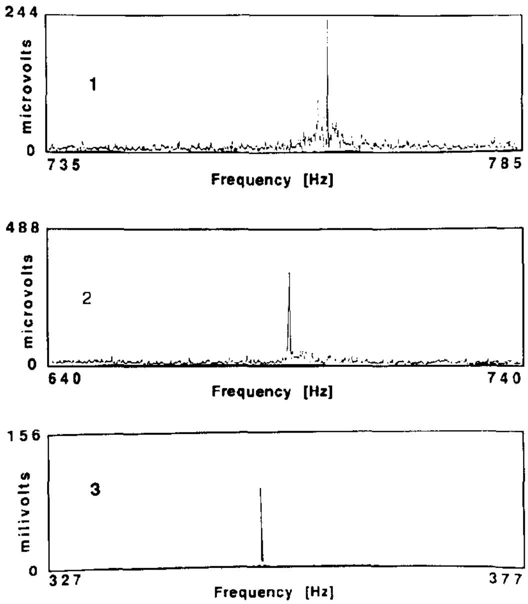

Fig. 5. Comparison of voltage signals corresponding to detected deflections for different cantilever beams: (1) bare Si; (2) Si covered with Au; (3) $ZnO/SiO_2/Si$.

The optomechanical effect can be used to determine the surface state parameters. Because of the large number of unknowns, surface state parameters cannot be deduced from simple measurements of the vibration frequency. Independent measurements of the barrier height and photovoltage transients [3] are required. In this work we were not able to perform all these measurements. Thus, an agreement between the experimentally determined amplitude of vibrations and eqn. (10) has been verified using the following experimental conditions:

resonant frequency of the beam 403 Hz;
light wavelength 514.5 nm;
total light power 6 μW;
piezoelectric constant of ZnO $d_{31} = 6.6 \times 10^{-12}$ m/V;
vibration amplitude 100 nm.

The vibration amplitude measured in this experiment can be described by eqn. (10) if the following parameters are used:

$p_\lambda = -10$, $p_0 = 25$
$\Delta V_s = 15.7$ mV

$K_{ph} = 4 \times 10^{-17}\ cm^2$
$L_c = 80\ nm$
$N_t = 10^{15}\ m^{-2}$

Only two parameters were arbitrarily chosen: K_{ph} and N_t. Other parameters were taken from the electrical characterization of the ZnO films. This shows that agreement between experiment and theory can be obtained using reasonable values of the surface state parameters. The surface state concentration at the air/Si interface can be lower than that at the grain boundaries as determined by electrical measurements. However, as has been mentioned earlier, some complementary measurements are needed for full characterization of the surface states.

Conclusions

Optically activated resonant vibrations based on the macroscopic photomechanical effect have been demonstrated. This effect, primarily observed in the depleted layer of non-centrosymmetric monocrystalline semiconductors, has been confirmed for the first time in polycrystalline ZnO exhibiting a high degree of (001) orientation perpendicular to the substrate. The concept of Blom and van de Pol for the low-frequency piezoelectric activity in the depleted layer of the magnetron sputtered ZnO films is in agreement with this work. High efficiency of energy conversion has been measured, which might lead to a new class of optically activated resonant sensors. These sensors can benefit from both the silicon micromachining technology and deposition techniques of ZnO films. The photomechanical effect can be a very efficient tool for studying the electrical properties of ZnO. A number of properties can be deduced from these measurements: energy position and concentration of the surface states, capture cross sections, depletion layer width etc. The comparison of experimental results and the theoretical description shows reasonable agreement. However, a very careful analysis of the experimental results and theory is required, because knowledge of the electrical properties of ZnO films is still insufficient. Moreover, a number of simplifying assumptions were necessary because of the complexity of the phenomena involved.

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